DIGITAL IMAGE CORRELATION

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Contents

Summary

The basic principle of digital image correlation for measuring surface displacement is described. The displacement components on the surface of an object are easily obtained using this method by recording the images of the surface before and after deformation. The effectiveness of this method is demonstrated by applying the method to the measurement of the displacement field around a crack tip, the measurement of strain distribution of shape memory alloys, and the bridge deflection measurement. Wide use of the method to various fields is expected because the measurement can be performed easily and simply.

1. Introduction

Experimental techniques in solid mechanics rely heavily on surface displacement field measurements. Several optical methods, such as moiré interferometry, holographic interferometry or speckle pattern interferometry have long been used in experimental solid mechanics to study mechanical deformation of solids and the mechanics of fracture. Among them, digital image correlation technique, which can obtain the deformation of a surface by comparison of digital images of the undeformed and deformed configurations, is becoming popular and widely used. Since this method does not need a complicated optical system, the measurement can be performed easily. In addition, unlike other methods which utilize the interference of light waves, phase analysis of the fringe pattern and subsequent phase unwrapping process are not required.

However, there are not only advantages but also drawbacks of this method. In this method, it is difficult to obtain reliable results around regions near boundaries such as around a crack surface since a subset, typically about 30 × 30 or 40 × 40 pixels in an image, is used to detect the deformation. For example, at a crack surface that subsets overlap with crack faces, the displacements are determined by areas on each side of the crack surface that have opposite displacements. The difficulty is found near stress concentration regions since it is assumed that the subset is deformed uniformly. Thus, the possible smallest size subset should be used to overcome these difficulties. An accurate digital image correlation method exists by taking the second order displacement gradients into account. However, the difficulty is still remaining since their method cannot reduce the subset size. Other efforts to improve the accuracy and the resolution have been made by several researchers.

The approach for determining surface deformation using digital image correlation technique has started from the 1980s and has long been developed by a research group at the University of South Carolina. Then, the technique has been improved by many researchers to increase resolution, to improve accuracy, and to overcome above drawbacks. Nowaday, many applications of this method to various problems can be found, such as in studies of fracture mechanics, high-temperature deformation measurement, bio-materials, wood products and inverse stress analysis. In recent years, this technique begins to be applied to the deformation measurement using images from Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM) and X-ray micro tomography.

In this article, the basic concept of digital image correlation is described. Then, the effectiveness of this method is demonstrated by applying the method to the measurement of the displacement field around a crack tip, the measurement of strain distribution arising in shape memory alloys, and the bridge deflection measurement. Wide use of the method to various fields is expected because the measurement can be performed easily and simply.

2. Two-dimensional Digital Image Correlation

2.1. Basic Principle

In two-dimensional digital image correlation, displacements are directly detected from digital images of the surface of an object (specimen). Figure 1 shows a typical example of an experimental setup for two-dimensional digital image correlation. The plane surface of an object is observed usually by a CCD camera with an imaging lens. Then, the images on the surface of the object, one before and another after deformation, are recorded, digitized and stored in a computer as digital images. These images are compared to detect displacements by searching a matched point from one image to another. Here, because it is almost impossible to find the matched point using a single pixel, an area with multiple pixel points (such as 20 × 20 pixels) is used to perform the matching process. This area, usually called subset, has a unique light intensity (gray level) distribution inside the subset itself. It is assumed that this light intensity distribution does not change during deformation. Figure 2 shows the part of the digital images before and after deformation. The displacement of the subset on the image before deformation is found in the image after deformation by searching the area of same light intensity distribution with the subset. Once the location of this subset in the deformed image is found, the displacement of this subset can be determined. In order to perform this process, the surface of the object must have a feature that allows matching the subset. If no feature is observed on the surface of the object, an artificial random pattern must be applied. Figure 3 shows a typical example of the random pattern on the surface of an object produced by spraying paint. The above concept is common among other techniques in digital image correlation.

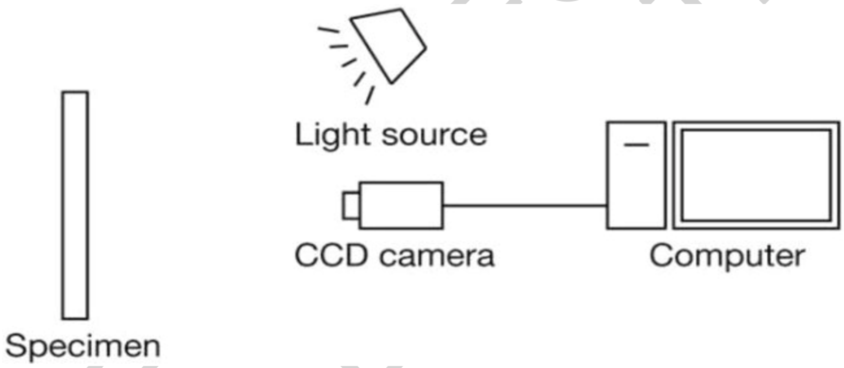

Figure 1 Setup for displacement measurement using digital image correlation

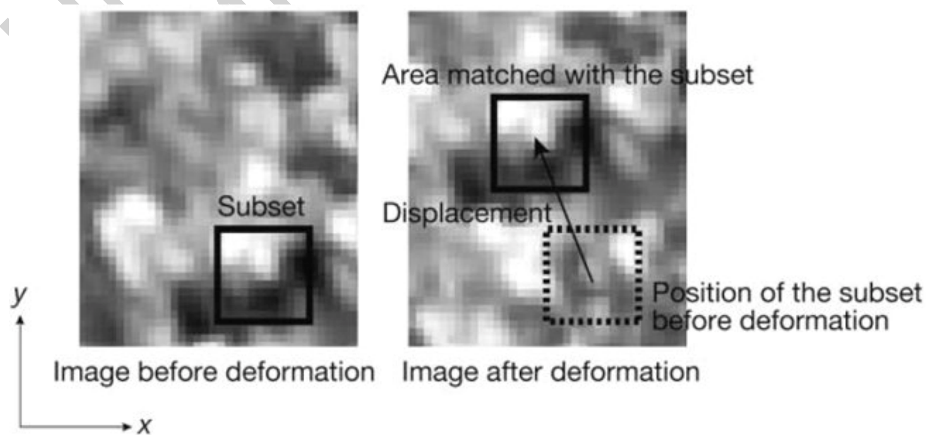

Figure 2 Matching the subset before and after deformation

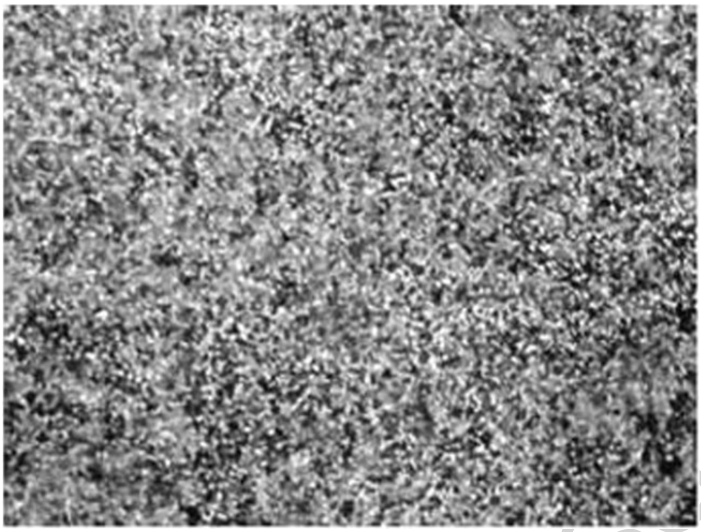

Figure 3 Typical example of random pattern on specimen surface

Based on the above basic concept, several functions exist to match the subset from one image to another. One is the magnitude of intensity value difference as

$$R(x,y,x^*,y^*) = \sum \left| F(x,y) - G(x^*,y^*) \right| \quad (1)$$

and another is the normalized cross-correlation as

$$C(x,y,x^*,y^*) = \frac{\sum F(x,y)G(x^*,y^*)}{\sqrt{\sum F(x,y)^2 \sum G(x^*,y^*)^2}} \quad (2)$$

where $F(x,y)$ and $G(x^*,y^*)$ represent the gray levels within the subset of the undeformed and deformed images, and (x,y) and (x^*,y^*) are the coordinates of a point on the subset before and after deformation, respectively. The symbol of the summation represents the sum of the values within the subset. The coordinate (x^*,y^*) after deformation relates to the coordinate (x,y) before deformation. Therefore, displacement components are obtained by searching the best set of the coordinates after deformation (x^*,y^*) which minimize $R(x,y,x^*,y^*)$ or maximize $C(x,y,x^*,y^*)$. Functions except for Eqs. (1) or (2) can be used, however, the normalized cross-correlation (Eq. (1)) is widely used for matching the subset in digital image correlation.

2.2. Estimating Displacements

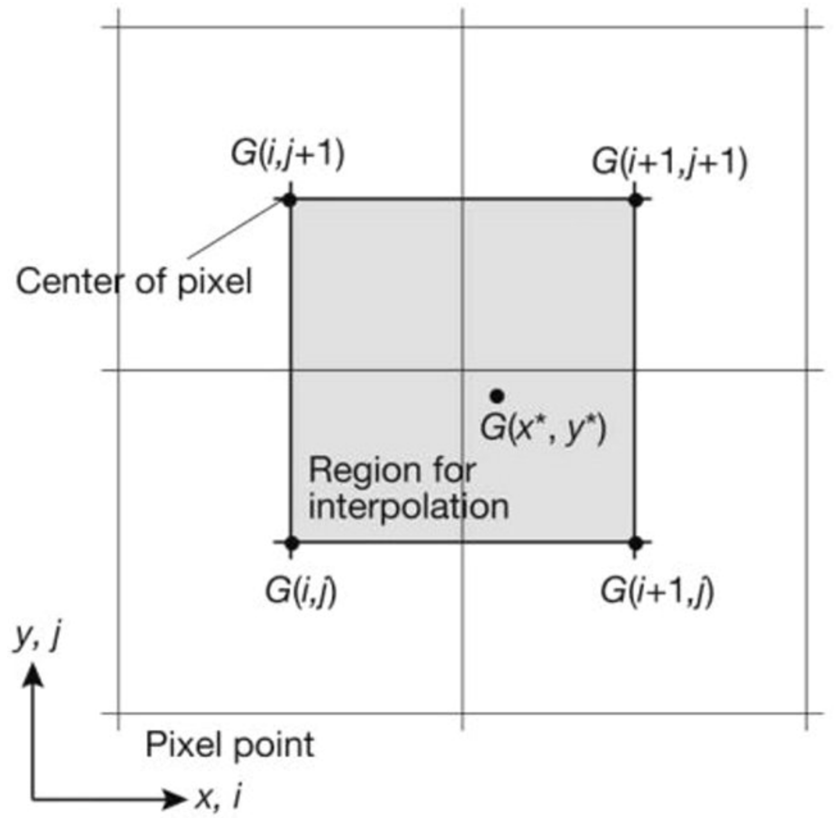

Figure 4 Pixel points and interpolating region for bilinear interpolation

The pixel points within the subset usually locate among the pixels on the deformed image. In addition, the subset can be deformed along with the deformation of the object's surface. In a digital image, gray values exist on discrete pixel points. In order to calculate the correlation on the position among pixel points and to allow the deformation of the subset, therefore, the values of gray level among the pixel points are required.

The simplest approach to obtain the value of gray level among the pixels is a bilinear interpolation. Figure 4 shows the neighboring four pixel points. It is assumed that the gray level of the pixel is the value at the center of the pixel. In this figure, four squares represent the four pixels, and $G(i, j), G(i+1, j), G(i, j+1)$ and $G(i+1, j+1)$ express the gray levels at the center points of the pixels. Here, $(i, i), (i+1, j), (i, j+1)$ and $(i+1, j+1)$ are the integer pixel positions. The gray level $G(x^*, y^*)$ at the point (x^*, y^*) among the integer pixel points is obtained as

$$G(x^*, y^*) = a_{00} + a_{10}x' + a_{01}y' + a_{11}x'y' \tag{3}$$

where x' and y' are the distance along the x and y direction from (i,j) to (x^*,y^*), that is, $x' = x^* - i$ and $y' = y^* - j$, and they lie in the rage of $0 \leq x' < 1$ and $0 \leq y' < 1$. a_{00}, a_{10}, a_{01} and a_{11} are the coefficients of the bilinear interpolation function. These coefficients can be determined from the gray levels at the integer pixel points as

$$
\begin{aligned}
a_{00} &= G(i, j) \\
a_{10} &= G(i+1, j) - a_{00} \\
a_{01} &= G(i, j+1) - a_{00} \\
a_{11} &= G(i+1, j+1) - a_{00} - a_{10} - a_{01}
\end{aligned}
\tag{4}
$$

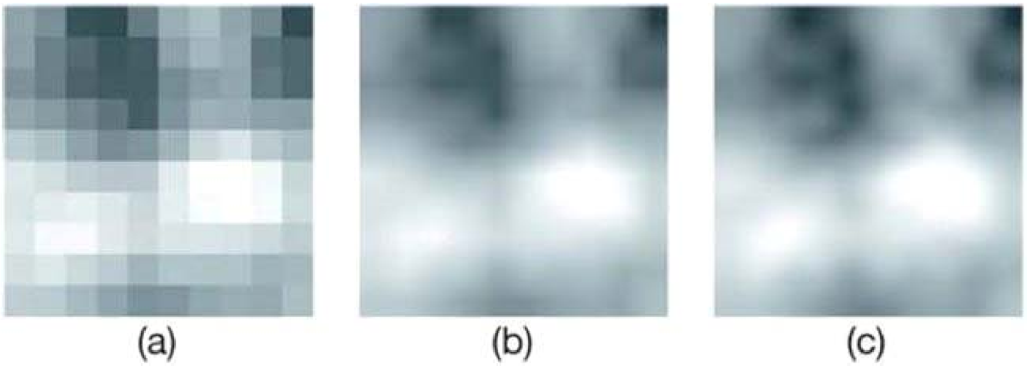

Figure 5 (a) 10 × 10 pixels region; (b) bilinear interpolation; (c) bicubic interpolation

Various interpolation methods other than the bilinear interpolation, such as bicubic interpolation and spline interpolation, have long been used. Not only the measurement accuracy but also the time for analysis is obviously dependent on the interpolation method. However, it is noted that the gray level obtained at a fractional pixel point by any interpolation technique is essentially not an actual value but just an interpolated and deduced value. Figure 5 shows a discrete 10 × 10 pixels region of an original image and the interpolated results by bilinear interpolation and bicubic interpolation. It is observed that continuous light intensity distribution is obtained by interpolation.

The coordinate (x^*,y^*) after deformation relates to the coordinate (x,y) before deformation. Assuming that the displacement gradients are constant throughout the subset, then the coordinate (x^*,y^*) is expressed as

$$
\begin{aligned}
x^* &= x + u_x + \frac{\partial u_x}{\partial x}\Delta x + \frac{\partial u_x}{\partial y}\Delta y \\
y^* &= y + u_y + \frac{\partial u_y}{\partial x}\Delta x + \frac{\partial u_y}{\partial y}\Delta y
\end{aligned}
\tag{5}
$$

where Δx and Δy are the x and y directional components of the distance from the center of the subset to the point (x,y) respectively. As a result, the subset deforms in the parallelogram as shown in Figure 6. In this figure, the center point P and the point Q on the undeformed subset move to the points P' and Q' on the deformed subset, respectively. Then, the moving distance from the point P to the point P' is interpreted as the displacement and the position of the point Q' is expressed as Eq. (5). It is noted that the displacement gradients, i.e., the strains are assumed as uniform within the subset. On the other hand, higher order displacement gradients can be used to express complicated deformation of the subset.

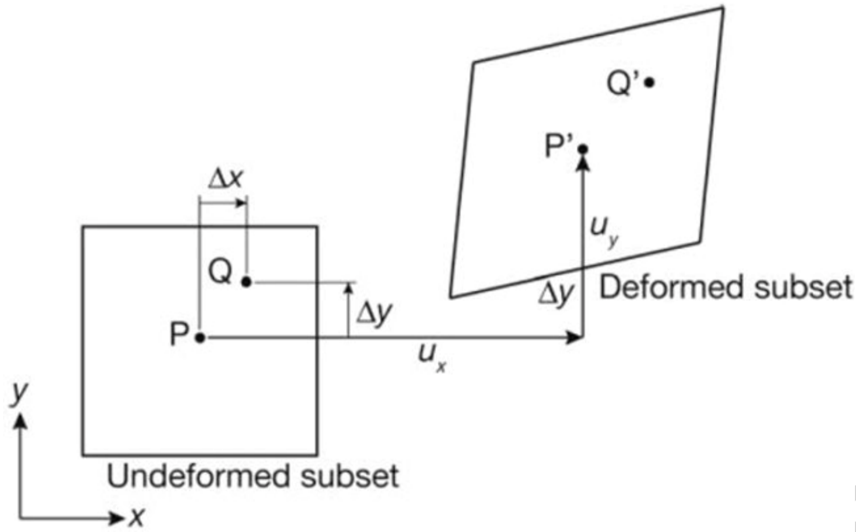

Figure 6 Subset before and after deformation

The correlation coefficient *C* in Eq. (2) is the function of the displacement components u_x and u_y, and the displacement gradients $\partial u_x/\partial x$, $\partial u_x/\partial y$, $\partial u_y/\partial x$, $\partial u_y/\partial y$. Therefore, the displacements are determined by searching the best set of the displacements and the displacement gradients, which maximize the correlation coefficient *C*. At first, the approximate displacements are estimated within the accuracy of one pixel with zero gradients. In this process, gray level interpolation is not needed. After the first estimation, the process varies to search both the displacements and the displacement gradients with gray level interpolation. Here, the following simultaneous equation that is obtained by differentiating Eq. (2) by the displacements and the displacement gradients is solved to find the extreme value of the correlation coefficient.

$$\begin{cases} \dfrac{\partial C}{\partial u_x} = 0 \\ \dfrac{\partial C}{\partial u_y} = 0 \\ \dfrac{\partial C}{\partial \left(\dfrac{\partial u_x}{\partial x} \right)} = 0 \\ \dfrac{\partial C}{\partial \left(\dfrac{\partial u_x}{\partial y} \right)} = 0 \\ \dfrac{\partial C}{\partial \left(\dfrac{\partial u_y}{\partial x} \right)} = 0 \\ \dfrac{\partial C}{\partial \left(\dfrac{\partial u_y}{\partial y} \right)} = 0 \end{cases} \qquad (6)$$

A numerical technique such as a Newton-Raphson method can be used to solve Eq. (7). In final, the displacements and the displacement gradients are obtained. It is noted that the displacement gradients are simultaneously calculated with the displacements in order to increase the accuracy of the displacements. Therefore, the displacement gradients themselves obtained by above procedure are not accurate to evaluate strains. If the second order displacement gradients are included to evaluate the displacements, the accuracy of first order displacement gradients may be improved.

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Biographical Sketches

Satoru Yoneyama was born in Isawa Town in Yamanashi Prefecture, Japan in 1972. He received his bachelor's and master's degrees from Aoyama Gakuin University in 1995 and 1997, respectively, and his PhD degree in mechanical and control engineering from Tokyo Institute of Technology in 2000.

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